Rapid Early Miocene exhumation of the Ladakh Batholith, western Himalaya.

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ABSTRACT

Zircon and apatite (U-Th)/He, and apatite fission track age data record a major rapid cooling event of the Ladakh Batholith of northwest India at c. 22 Ma. Combining the thermochronometric data with structural evidence it is proposed that exhumation was due to south-directed overthrusting of the Batholith. This thrust is potentially an extension of the Gangdese Thrust which accommodates underthrusting of the Gangdese Batholith in southern Tibet. The rapid exhumation recorded in Ladakh is contemporaneous with exhumation of the High Himalaya. This focused denudation and structural shortening north of the Indus Suture Zone in early Miocene times implies that the actively deforming and eroding Himalayan thrust wedge extended further north than channel flow models currently predict.

INTRODUCTION

The Himalayan mountain chain is bordered to the north by a line of arc-derived batholiths known as the Trans-Himalayan Plutonic Belt that stretch 2500 km from Afghanistan in the west to Bhutan (Honneger et al., 1982). Prior to collision at approximately 55 Ma, there was extensive oceanic subduction northward beneath the Plutonic belt now preserved as slivers of ophiolite in the Zanskar Range (Searle et al., 1997; Makovsky et al., 1999). Whether the Trans-Himalayan Plutonic belt continued to be underthrust after collision with the Indian plate, or acted as an underformed backstop, is an important component of the tectonic history of the orogen (eg. England and Searle, 1986). In southern Tibet, there is compelling evidence for post-collisional underthrusting of the Gangdese Batholith where it is bound to the south by the Gangdese Thrust, a major north-dipping shear zone (Yin et al., 1994).

Thermochronometric data indicate a punctuated cooling history for the Gangdese Batholith with a period of accelerated erosion in early Miocene times in response to southward motion along the Gangdese Thrust (Copeland et al., 1995). Whether the entire Trans-Himalayan Plutonic Belt has also experienced southward thrust shortening with a similar cooling history is unclear, but is critical if this structure is to be considered of local or of orogen-wide significance. Models of channel flow coupled to surface denudation have suggested extrusion of the High Himalayas in early Miocene times (Beaumont et al., 2001), ie. synchronous with the suggested motion on the Gangdese Thrust (Yin et al., 1994). Whether the region north of this extruding channel represented a passive lid, or was actively deforming and eroding, as suggested by the presence of the Gangdese Thrust is a significant constraint for channel flow models. This study aims at extending our understanding of this potentially important structure.

The Ladakh Batholith in northwest India represents the most distant, along-strike equivalent to the Gangdese Batholith. If the southward thrusting of the Trans-Himalayan Plutonic Belt is orogenic in scale, we should expect to record evidence of it in the Ladakh region. Here, we test for the presence of southward overthrusting of the Ladakh Batholith by integrating the regional structural geology of the area with the first detailed thermochronometric study of the Batholith. This approach utilises fission track and (U-Th)/He in apatites with (U-Th)/He in zircons from multiple samples over a large elevation range enabling evolving rates of cooling to be assessed (eg. Fitzgerald et al., 1995; Reiners et al., 2002).

REGIONAL SETTING

The Ladakh Batholith is located between two major tectonic suture zones; the Shyok to the north and the Indus-Tsangpo to the south (Fig. 1). The former represents a collisional boundary between the Karakoram terrane and the island arc, and the latter represents the main boundary zone between the Indian and Eurasian plates (Searle et al., 1990). A thick pile of sediments, the Indus Molassse, drape the boundary between the Ladakh Batholith and the Indus Suture zone and record fore-arc and intermontane basin development (Garzanti and Van Haver, 1988; Sinclair and Jaffey, 2001). In the eastern part of the study area, the Batholith is bound to the northeast by the Karakoram Fault, a major dextral strike-slip fault that bounds the south-western margin of the Tibetan Plateau (Fig. 1), and has been active since Miocene times (Searle et al., 1992). U-Pb crystallisation ages from the main Batholith range from 65 to 49 Ma (Weinberg and Dunlap, 2000), suggesting that magmatism was contemporaneous with the Gangdese Batholith (Scharer et al., 1984) and that magmatic activity ceased with the collision of India and Eurasia. Apatite fission track

(AFT) ages of the Ladakh Batholith from Kargil to Chumatang range from 28 to 4.8 Ma (Choubey, 1987; Sorkhabi et al., 1994; Clift et al., 2002; Schlup et al., 2003). The young Pliocene ages are related to minor faulting (Choubey, 1987), however, there remains a spread in single AFT ages from 18 to 28 Ma (Sorkhabi et al., 1994; Clift et al., 2002). How these ages record the detailed history of exhumation of the Batholith is not clear due to the broad scatter of the samples.

THERMOCHRONOMETRY

In rapidly cooled rocks zircon fission track (ZFT) and zircon He (ZHe) thermochronometers record the cooling history of rocks below 230°C and 180°C respectively (Brandon et al., 1998; Reiners et al., 2004). The apatite FT and apatite He (AHe) thermochronometers are sensitive to the temperature intervals of 110 to 80 °C and 75 to 40°C respectively, with closure temperatures of 110 °C and 68 °C in rapidly cooled rocks (Farley et al., 1996; Gallagher et al., 1998). For normal crustal geothermal gradients of 20 – 40 °C/km these thermochronometers provide quantification of the time rock masses pass through the upper 1-6 km of the Earth's crust (Reiners et al., 2002; Ehlers and Farley, 2003).

The samples analysed here are granites and granodiorites from a steep elevation profile from northwest of Leh to the drainage divide along the Khardung La route (Fig. 1). This region has a vertical extent of just over 1.3 km, from 3921 to 5245 m.a.s.l., over a horizontal distance of 10 km. The profile is between sites of previous studies (Choubey et al., 1987; Sorkhabi et al., 1994; Clift et al., 2002; Schlup et al., 2003). Only sample KHARS 5245 from the top of the profile was analysed using all techniques. AFT analyses were made on six samples. ZHe ages were obtained from the top (5245 m), middle (4552 m) and bottom (3921 m) of the profile while AHe ages were obtained from the three samples where inclusion-free grains could be picked. Analytical methods and data tables are reported in Appendix 1.

RESULTS

All fission track and (U-Th)/He ages are considerably younger than the Eocene crystallisation ages of the Batholith (Weinberg and Dunlap, 2000). The single ZFT analysis for sample KHARS 5245 from the top of the near vertical profile provides a late Oligocene pooled fission track age of 26.2 ± 1.8 Ma (Fig. 2a). ZHe ages are Early Miocene ranging from 24.5 Ma (top) to 20.7 Ma (bottom) (Fig. 2a).

Samples from the top (5245 m) and bottom (3921 m) of the Leh to Khardung La traverse have invariant AFT ages at approximately 22 Ma (Fig. 2a). The error on the FT age of the bottom sample is large due to the low apatite concentration in the sample and low spontaneous track density. Between these two samples some scatter is observed with individual ages ranging from 23 to 18 Ma, although all samples are within the two sigma range of the lowest sample (Fig. 2a). There are no obvious variations in apatite compositions based on dpar values. In general all AFT samples have long mean track lengths with tight distribution curves indicating that the host rocks underwent rapid transport through the partial annealing zone (Fig. 2).

Apatite He ages are younger than, or indistinguishable from, the AFT ages (Fig. 2a). Duplicate He ages were measured on three samples from the profile with only the uppermost sample not replicating within 1 sigma analytical uncertainty. Neglecting the apparently old age from sample KHARS 5245, apatite He ages range from 15.5 Ma to 12.2 Ma (Fig. 2a).

THERMAL HISTORY

Given the lack of any extensional faulting in this region, the fission track and (U-Th)/He ages record cooling due to the erosional unroofing of the Ladakh Batholith. The ZHe ages are within error of the measured AFT ages suggesting that the region has undergone a period of rapid exhumation in early Miocene times at approximately 22 Ma. For geothermal gradients typical of orogenic belts (20 - 40 °C/km) the preservation of similar ZHe and AFT ages over 1300 m elevation requires that between 2 and 5 km of material was removed in the Early Miocene. If the ZFT age from sample KHARS 5245 is included then between 3 and 6 km of material has been removed from that part of the profile. The ZFT, ZHe and AFT data presented here indicate a rapid phase of exhumation in late Oligocene-early Miocene times that has not previously been recognised in this region. Such rapid exhumation will have strongly distorted shallow isotherms in a region of such impressive topography (e.g. Stuwe et al., 2000). Thus, interpreting the thermal history from the apatite (U-Th)/He age-elevation relationship is problematic.

Thermal history information was extracted by modelling AFT grain ages and track lengths using AFTSolve (Ketcham et al., 2000) (Fig. 2b). The modelled thermal histories indicate a period of rapid cooling from approximately 25 to 15 Ma (Fig. 2b) and suggest that from mid Miocene times cooling has slowed to less than c. 3.5 °C/Myr (Fig. 2b). Such a rate is consistent with historic erosion rates of 0.05 ± 0.05 mm/year measured for the region using sediment yield studies from lake records (Garzanti et al. 2005). This decrease is qualitatively consistent with the younger AHe ages from the profile. However, the thermal modelling of track lengths is not well constrained above the apatite closure temperature (~80 °C, Gallagher et al., 1998) and so shallow events which might be otherwise captured using apatite He age dating may not be evident. Indeed the measured apatite He ages are mid Miocene over an elevation range of > 700 m which potentially suggests exhumation was rapid between 13 and 15 Ma. Unfortunately the data did not permit the distinction between the influence of isotherm warping due to rapid exhumation at 22 Ma or a second pulse of exhumation. Simple forward modelling using the data available and the DECOMP program (Meesters and Dunai, 2002) suggests that the data do not require a pulse at 13-15 Ma.

Combining the results presented here, together with previously published Ar-Ar cooling ages from further west, suggests an episodic exhumation history for the Batholith (Fig. 3). Hornblende and biotite $^{40}Ar/^{39}Ar$ cooling ages indicate an initial rapid phase of exhumation during the late Eocene (Clift et al., 2002). The difference in age between the biotite $^{40}Ar/^{39}Ar$ ages (49 – 44 Ma; Clift et al. 2002) and the ZFT data (26 Ma) imply that the exhumation rate has decreased from the late Eocene to the late Oligocene (Fig. 3). Exhumation then accelerated dramatically for a period in the late Oligocene - early Miocene followed by a marked deceleration which has continued to the present day (Fig. 3). The rapid Early Miocene exhumation could either represent accelerated erosion rates due to a more erosive climate or due to increased rates of rock uplift linked to regional deformation. Reconstructing past climates within mountain belts is difficult, and currently, there is no evidence to suggest any significant change in the climate around 22 Ma in this region. Strengthening of the monsoon across the region is thought to occur in the mid Miocene times based on offshore sediment records (Clift et al., 2001). Hence, we focus here on the potential structural explanation for this earlier erosional history.

STRUCTURAL SETTING OF THE LADAKH BATHOLITH

There is little evidence of significant shearing or faulting within the Ladakh Batholith with the exception of the Thanglasgo Shear Zone in the north of the Batholith that comprises a thick zone of mylonites (Weinberg et al., 2000). The northern margin of the Batholith is overlain by the Khardung volcanics which dip at approximately 60 degrees north-northwestward (Fig. 4), and which are locally highly deformed, and yet rest conformably on the underlying granodiorite of the Batholith (Weinberg et al., 2000).

The southern-most margin of the Ladakh Batholith is either onlapped by sediments of the Indus Molasse, or by broad accumulations of recent alluvial fan sediments (Garzanti and Van Haver, 1988; Jamieson et al., 2004). The Indus Molasse has been intensely deformed, with the youngest part of the succession recording north-northeastward thrusting and folding which is considered the northern limit of Zanskar backthrusting (Corfield and Searle, 2000) (Fig. 4b). The older part of the succession additionally records an earlier, south-vergent phase of deformation comprising large scale folding and a slatey axial planar cleavage (Fig. 4b). Interference folds and folded thrust planes are generated where this earlier deformation is overprinted by the later north-vergent deformation that dominates the younger part of the succession (Sinclair and Jaffey, 2001).

The combined evidence of early, southward-vergent deformation of the Indus Molasse with the northward tilting of the Khardung Volcanics suggests that the Batholith was overthrust towards the south-southeast along a northwardly inclined thrust plane, similar to the Gangdese Thrust to the east (Yin et al., 1994). Therefore, we believe that the Gangdese Thrust was a major, northward dipping structure that was responsible for the Early Miocene deformation of the Trans-Himalayan Plutonic

Belt over 800 km from the central Himalayas of Nepal to the western Himalayas of Ladakh.

WIDER GEOLOGICAL IMPLICATIONS

The Main Central Thrust (MCT) which separates High Himalayan crystalline rocks from the Lesser Himalayas was initiated and active between 23 and 17 Ma (Hodges, 2000; Stephenson et al., 2001). Leucogranites formed by crustal melting have contemporaneous Early Miocene crystallisation ages (Noble and Searle, 1995). This has been used to propose that rapid exhumation of the High Himalayas by thrusting on the MCT occurred during early Miocene times (~22 Ma). The northern margin of the High Himalayas is defined by the South Tibetan Detachment (STD) (locally known as the Zanskar Detachment in the Ladakh region). This normal fault has been active since the Early Miocene (e.g. Yin and Harrison 2000; Waters et al., 2004) with onset of rapid exhumation at 22-21 Ma (Waters et al., 2004). Movement on the MCT and STD system predates Zanskar backthrusting in the mid to late Miocene (Searle et al., 1997). The thermochronometric data and the structural evidence in Ladakh suggests that a thrust, potentially the westward extension of the Gangdese Thrust, drove rapid unroofing of the Trans-Himalayan Plutonic Belt during early Miocene times, synchronous with the movement on the MCT and STD. It is thus contemporaneous with rapid exhumation of the High Himalayas demonstrating that the region to the north of the extruding channel flow was actively uplifting and eroding. Given that the input parameters for the channel flow model require localised high denudation rates over the High Himalaya (Beaumont et al., 2004), the recognition of high erosion rates and contemporaneous compressional deformation to the north suggests that the parameterisation of these models should be revised.

CONCLUSIONS

Accelerated Early Miocene erosion of the Ladakh Batholith of the western Himalaya occurred in response to rock uplift along a major-northward dipping thrust that underlies the Batholith. The thrust emerged south of the Batholith, and caused south-vergent deformation of the Indus Molasse. This phase of erosion and deformation deceased soon after 20 Ma, prior to northward vergent Zanskar backthrusting. These events were synchronous with activity on the Gangdese Thrust, the South Tibetan Detachment system and the MCT. Therefore, it appears that the Gangdese Thrust was an orogen-wide structure of broad significance in Himalayan evolution. Furthermore the recognition of orogen-wide deformation and rapid erosion north of the Indus Suture Zone increases the overall width of the actively deforming wedge during the period of channel flow through the High Himalaya in Early Miocene times.

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Figure captions

Figure 1. Regional geological summary of the Himalayas highlighting the location of the Trans-Himalayan Plutonic Belt. Proposed and documented locations for the Gangdese Thrust are shown from Yin et al., 1994 and Copeland et al., 1995.b. Detail of western Himalaya showing the sample area and cross-section illustrated in figure 4.

Figure 2. a. Age – elevation profile for samples from the near-vertical profile. Thermochronometers include zircon fission track (grey square), zircon He (open square), apatite fission track (grey circle) and apatite He (open circle). Inset are track length distribution profiles for all samples. Inset graphs show track length distributions in microns along the x-axis and normalised frequency along the y-axis. All graphs have same scales. The numbers represent the elevation of the sample and the mean track lengths. b. Thermal histories for all samples dated by apatite fission track generated using AFTSolve (Ketcham et al., 2000). Note steep gradients of all profiles through the apatite partial annealing zone (PAZ). PRZ = Partial retention zone for apatite He.

Figure 3. Temperature – time history for the Ladakh Batholith as constrained by the different thermochronometers applied here and by Clift et al. (2002).

Figure 4. Regional cross-section through the western Himlaya showing the possible location of a remnant northward dipping thrust beneath the Ladakh Batholith overprinted by the backthrusting of the Indus Molasse succession. b. Enlarged section of the Indus Molasse highlighting the important early south-vergent deformation,

which is overprinted by later north-vergent deformation (modified from Sinclair and Jaffey, 2001).

Supplementary Information.

Analytical Methods.

Apatite and zircon separates were prepared from the 100-150 μm fraction of each rock and analysed for fission tracks at Donelick Analytical Inc. The fission track ages presented here are pooled ages with 1-sigma errors (Table 1). There is no systematic variation in apatite composition, all are F-rich apatite and etch pits are generally of uniform size (0.45 ± 0.05 μm). Where greater than 100 tracks were counted, track length distributions are relatively uniform, with mean track lengths ranging from 13.8 to 14.4 μm, with standard deviations of 1.5-1.9 μm (Table 1). The sample where less than 25 tracks were counted yielded a lower mean track length of 13.2 ± 1.8 μm.

Apatite He age determinations follow the procedure established by Balestrieri et al. (2005). From the apatite separates prepared for fission track analyses, inclusion-free apatites were picked using a binocular microscope for (U-Th)/He age determinations. For each sample between 3 and 9 prismatic grains varying in diameter from 75 to 200 μm were loaded into re-usable stainless steel capsules. A single inclusion-free zircon crystal from sample KHARS 3921 was loaded into a platinum tube and packed into a stainless steel capsule. Each capsule was heated in a resistance furnace at 950°C (apatite) and 1190°C (zircon) for 30 minutes. The remaining zircon samples were packed into Pt tubes and heated using an 808 nm diode laser following established protocols (Foeken et al. submitted). ^{4}He concentrations were measured relative to a 99.9% pure ^{3}He spike in a Hiden HAL3F quadrupole mass spectrometer equipped with an electron multiplier detector at SUERC. After each measurement samples were reheated to ensure complete degassing. Following analysis sample capsules were retrieved and the apatites dissolved in ^{235}U- and ^{230}Th-spiked nitric acid. The retrieved

Pt-enclosed zircon was spiked with ^{235}U and ^{230}Th before being dissolved in a Parr™ bomb dissolution vessel. The ion exchange column chemistry of Luo et al. (1997) was used to remove the Pt and separate the U and Th. U and Th concentrations were measured on a VG PlasmaQuad 2 ICPMS. Correction for helium recoil loss was made using the procedure of Farley et al. (1996) and Hourigan et al. (2005). Zoning of the apatites was checked using the fission track distribution. The majority of apatites are unzoned or show minor zoning. Analytical uncertainty for each sample is 3-6%.

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